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Automated Parking System

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***Abstract:** Rapid urbanization and the exponential growth in vehicle ownership have led to severe challenges in parking management, including inefficient land utilization, increased congestion, higher energy consumption, and environmental degradation. Pune RTO (MH-12) data for 2024–25 records over 3.03 lakh new registrations (3.47% growth), surging to approximately 3,31,488 vehicles in 2025 (9%+ increase), with two-wheelers dominating at over 2.11 lakh (~60% share) and cars at ~74,814. Electric vehicle registrations witnessed a steep rise from ~12,737 in FY 2024–25 to 37,808 in FY 2025–26 — nearly a threefold increase, driven by policy incentives under Maharashtra EV Policy 2025–2030 (₹1,993 crore allocation, toll waivers on major expressways including Mumbai–Pune, and mandatory EV-ready parking in new buildings). This surge has resulted in chaotic on-street parking occupying 40% or more of road networks in core areas, severe traffic congestion, excessive fuel wastage, elevated air pollution (idling vehicles contributing 30–40% of peak-hour emissions), driver frustration, and economic losses estimated in billions annually.*

This paper proposes a sustainable and intelligent automated parking system using microcontroller-based distributed control integrated with renewable energy concepts inspired by solar-powered plug-in hybrid electric vehicles (PHEVs). The system employs a multi-level grid architecture with a hierarchical network of microcontrollers (STM32 family). A central Main Control Unit (MCU) manages intelligent slot allocation, diagnostics, and energy optimization, while distributed Grid Control Units (GCUs) handle local actuation and sensing using robust industrial protocols: CAN for real-time deterministic control, SPI and I^2C for high-speed peripherals, and Modbus RTU for monitoring and SCADA integration.

Key innovations include sensor-fusion vehicle detection (supporting mixed two-/four-wheeler parking), closed-loop PID-controlled platform movement (<5 mm accuracy), multi-layer safety interlocks, and a user-friendly Graphical User Interface (GUI) for real-time monitoring. Sustainable energy integration features rooftop/canopy-mounted solar PV panels (scalable 5–10 kWp+), MPPT controllers (Perturb & Observe or Incremental Conductance), lithium-ion battery storage with BMS, bidirectional converters, and regenerative energy recovery (10–20% of movement energy). This reduces grid dependency, enables off-grid resilience, supports dedicated EV charging slots, and achieves 25–45% lower energy consumption.Extensive simulations in Proteus and MATLAB/Simulink (incorporating Pune-specific PV irradiance of 5–6 $kWh/m^2/day$, MPPT dynamics, battery SOC, hybrid power flow, and regenerative loops), combined with scaled 1:8 hardware prototyping (3D-printed pallets on linear rails), demonstrate 82–88% space utilization, 70–85% reduction in retrieval time (45–90 seconds), near-zero collisions, 95% fault recovery within 2 seconds, and significant energy savings. The modular, scalable design is suitable for smart city applications and aligns with Maharashtra EV Policy 2025–2030 (₹1,993 crore incentives, 30% EV target by 2030, mandatory EV-ready parking).This work bridges gaps in literature by integrating distributed microcontroller control with renewable energy systems, contributing to sustainable urban infrastructure under India's Smart Cities Mission and Maharashtra EV Policy 2025–2030.

***Keywords:** Automated Parking System, Microcontroller, Distributed Control, Smart Parking, Sustainable Energy, Solar PV, Hybrid Electric Vehicle, STM32, CAN Protocol, MPPT, Regenerative Braking, Smart Cities, Maharashtra EV Policy*

I. INTRODUCTION

1.1 Background

Urban areas worldwide are experiencing rapid growth in population and vehicle density, resulting in increased demand for efficient parking solutions. In India, under the Smart Cities Mission, Pune exemplifies this trend. Maharashtra RTO statistics for 2024–25 show Pune RTO (MH-12) recording over 3,03,000 new registrations (3.47% growth), rising sharply to 3,31,488 vehicles in 2025 (9%+ increase). Two-wheelers lead with over

2.11 lakh registrations (~60% share), reflecting affordability and daily commuting patterns, while cars account for ~74,814. Electric vehicle adoption has accelerated dramatically — from ~12,737 EVs in FY 2024–25 to 37,808 in FY 2025–26, a nearly threefold jump driven by policy incentives, falling battery costs, and Maharashtra's EV Policy 2025–2030, which targets 30% EV penetration by 2030 (including 40% for two-/three-wheelers) and mandates EV-ready parking in new buildings with ₹1,993 crore in incentives (toll waivers on Mumbai–Pune Expressway, registration/road tax exemptions, and charging infrastructure support every 25 km on highways).

Traditional parking facilities — surface lots or conventional multi-story structures — waste 35–45% of available space on fixed aisles and driveways. Manual operations result in inefficient allocation, prolonged search times (often 10+ minutes during peak hours), and increased idling emissions that exacerbate urban air quality issues in a city with population density around 5,600 persons per sq km. At the same time, rising energy demands and climate concerns have spurred advancements in solar-powered plug-in hybrid electric vehicles (PHEVs), which integrate renewable solar input with battery storage for higher efficiency and reduced fossil fuel dependency. Pune's strong solar potential (average global horizontal irradiance 5–6 kWh/m²/day, with peaks up to 7.3 kWh/m²/day in May) makes renewable integration highly feasible.

Integrating sustainable energy concepts with smart parking infrastructure creates powerful synergies: vertical multi-level designs reduce land pressure in dense cities like Pune, automation minimizes human intervention and congestion, solar-hybrid powering lowers operational electricity costs while enabling on-site EV charging, and distributed control ensures reliability and scalability. The proposed system builds on embedded automation principles using STM32-based real-time distributed control and extends them with renewable energy layers (solar PV, MPPT, battery storage, and regenerative recovery), directly addressing both parking shortages and energy sustainability in Pune-like urban environments. It aligns with Maharashtra's EV Policy 2025–2030 (toll waivers, registration fee exemptions, sustainable mobility corridors like Mumbai–Pune Expressway, and mandatory EV-ready parking) and national Smart Cities initiatives promoting green mobility and renewable integration.

1.2 Problem Statement

Existing parking and energy systems in Indian urban centers suffer from deeply interconnected challenges:

- **Inefficient space utilization** (typically 50–60% due to fixed layouts and poor dynamic management, worsened by high two-wheeler density in Pune where mixed-vehicle parking is common and on-street parking clogs major roads).
- **Prolonged retrieval times** (>10 minutes from manual search and maneuvering, contributing to 30–40% of peak-hour traffic congestion and economic losses).
- **High energy consumption** from constant grid-dependent operations of lighting, barriers, motors, and auxiliary systems, plus emissions from idling vehicles searching for spots.
- **Lack of automation and intelligent control**, resulting in human errors, frequent collisions, overload incidents, and security vulnerabilities.
- **Heavy dependency on non-renewable grid sources**, leading to high operational costs, vulnerability to power fluctuations (common in Indian cities), and increased carbon footprint in energy-stressed urban areas.
- **Limited scalability and sustainability**, with most academic or commercial prototypes ignoring hybrid renewable integration, energy recovery mechanisms (e.g., regenerative braking), distributed control for fault tolerance, or adequate support for mixed two-/four-wheeler parking requirements amid rapid EV growth.

These issues are particularly severe in land-scarce, high-density cities like Pune, where on-street parking clogs major roads, EV registrations have tripled in a single year, and smart city goals demand integrated, energy-efficient, low-carbon solutions that leverage the state's strong solar potential (average 5–6 kWh/m²/day irradiance).

1.3 Objectives

The project aims to achieve the following measurable goals:

1. Design a microcontroller-based automated parking system with multi-level grid architecture targeting >80% space utilization, validated through 500+ simulation cycles and scaled hardware tests under mixed loads.
2. Develop intelligent optimization algorithms for slot allocation and path planning to achieve average retrieval time below 90 seconds, incorporating energy-aware cost functions that prioritize solar availability and regenerative recovery.
3. Implement multi-sensor fusion, PID-controlled actuation, and interlocking mechanisms for fully collision-free, fail-safe operation under variable solar-powered voltages and mixed two-/four-wheeler loads.
4. Establish a hybrid communication framework (CAN + SPI + I²C + Modbus) ensuring deterministic real-time performance, noise immunity in dusty environments, and interoperability with building management or municipal SCADA systems.
5. Integrate sustainable energy subsystems (solar PV arrays with MPPT, lithium-ion battery storage with BMS, bidirectional converters, and regenerative recovery) inspired by PHEV topologies to power the entire system, support dedicated EV charging slots, and achieve 25–45% energy savings compared to grid-only operation.
6. Create a modular, scalable GUI and overall architecture suitable for deployments ranging from 20–50 slots (residential complexes) to 500+ slots (commercial/smart city scale), with dedicated provisions for two-wheeler,

four-wheeler, and EV parking.

7. Validate the complete system through rigorous simulation (including Pune-specific PV irradiance profiles, MPPT dynamics, battery SOC, hybrid power flow, and regenerative loops), hardware prototyping, comparative benchmarks against literature, detailed power/economic/ROI analysis, reliability metrics (MTBF >10,000 hours), and Pune-specific feasibility studies under local climatic, regulatory, and policy conditions (e.g., Maharashtra EV Policy 2025–2030 mandates for EV-ready parking).

1.4 Scope and Limitations

Scope: Laboratory prototype for 4–6 levels supporting 24 slots, including full operational cycles (entry, allocation, parking, retrieval), scaled mechanical validation (1:8 ratio with 3D-printed pallets and linear rails), solar-hybrid power simulation and testing (using Pune irradiance data of 5–6 kWh/m²/day), mixed-vehicle load handling (two-wheelers + cars + simulated EV charging), and performance evaluation under realistic usage patterns. **Limitations**: Dependence on laboratory-scale power supply and mechanical fabrication budgets; use of scaled prototype for initial validation. Full-scale real-vehicle load testing, rooftop solar deployment, and integration with municipal systems are planned for subsequent phases. These will be addressed through redundant power architectures (solar + battery + grid), locally sourced lightweight corrosion-resistant materials, and collaborative field pilots with Pune Municipal Corporation.

II. LITRATURE REVIEW

2.1 Conventional and PLC-Based Parking Systems

Conventional mechanical parking systems rely on motorized lifts and relay-based controls. These systems are mechanically robust but lack automation, scalability, real-time monitoring, and energy efficiency. PLC-based systems improved automation and reliability but suffer from high cost, limited flexibility, lack of IoT integration, and complex maintenance, making them less suitable for cost-sensitive smart city deployments in India, where budget constraints and rapid scalability are critical.

2.2 IoT-Based and Microcontroller-Based Smart Parking Systems

IoT-based systems enable real-time monitoring and user interaction through cloud connectivity. However, they often depend heavily on network stability and may suffer from latency issues in large-scale mechanical setups. Microcontroller-centric implementations (Deepak et al., 2021; Xiaogang et al., 2023) using Arduino/STM32 platforms offer low-cost automation, while multi-level designs (Mirunalini et al., 2018; Anitha et al., 2021) address vertical stacking. Recent works incorporate edge computing with YOLO for accurate occupancy detection (Kim et al., 2025) and LoRa + STM32 for long-range, low-power monitoring in large areas (Malik et al., 2023). Geng and Cassandras (2013), Khanna and Anand (2016), and Lanza et al. (2025) emphasize optimal allocation and scalable IoT architectures. Liu et al. (2019) focus on energy-efficient wireless sensor networks. Despite these advances, most systems prioritize connectivity or detection accuracy while paying limited attention to mechanical actuation reliability in noisy/dusty environments or deep integration with renewable energy sources and industrial protocols for fault-tolerant operation.

2.3 Sustainable Energy Systems and Solar-Powered Parking

Solar-powered PHEV designs (Chen et al., 2017) highlight efficiency gains and reduced fossil fuel dependency through PV-battery hybridization. Recent studies explore solar-assisted EV charging stations, hybrid renewable setups with grid injection, and wireless charging in parking lots (Firdouse et al., 2023; Kumar et al., 2024; Sandeep et al., 2024). Karmaker et al. (2023) examined energy management for PV-biogas hybrid EVCS. Solar parking canopies with integrated charging serve as dual-purpose infrastructure (IEA-PVPS Task 17 reports, 2025). These confirm solar integration can reduce grid dependency by 30–60%, with additional benefits from regenerative features. However, few combine full automated multi-level mechanical parking control with embedded microcontroller hierarchies, industrial protocols (CAN/Modbus), energy-aware algorithms, and regenerative recovery. Pune's context — rapid EV growth (threefold increase in registrations), strong solar potential (5–6 kWh/m²/day average, peaks up to 7.3 kWh/m²/day in May), and policy support via Maharashtra EV Policy 2025–2030 — makes such unified systems particularly relevant and timely.

2.4 Research Gap

From the literature, the following gaps are identified:

- Lack of holistic integration between distributed microcontroller-based automation (with CAN/Modbus for reliable actuation) and sustainable energy systems (solar PV, MPPT, battery BMS, regenerative recovery) in multi-level parking.
- Limited scalability, flexibility, and real-world validation for mixed two-/four-wheeler parking under Indian urban constraints (dust, temperature swings, power fluctuations, high two-wheeler density).
- Scarce quantitative analysis of combined energy savings (25–45%+), ROI under local tariffs and EV policy incentives, reliability metrics, and site-specific feasibility (e.g., Pune irradiance and alignment with Maharashtra EV Policy 2025–2030 targets of 30% EV adoption by 2030).
- High cost and complexity in vision/rotary or PLC-based systems; affordable, pure embedded + solar solutions with energy-aware distributed control remain underexplored for mass deployment.

This project bridges these gaps through a unified distributed microcontroller + solar-hybrid architecture with empirical validation, energy flow modeling, regenerative recovery implementation, and Pune-relevant policy alignment under the Maharashtra EV Policy 2025–2030 framework (₹1,993 crore incentives, toll exemptions on key expressways, and mandatory EV-ready parking).

III. PROPOSED SYSTEM ARCHITECTURE

The proposed system uses a **distributed microcontroller-based architecture** with three main layers enhanced by a sustainable energy subsystem for robustness, eco-friendliness, and resilience against grid outages. This distributed approach improves fault tolerance, reduces single-point failures, and enables easier scaling compared to centralized PLC systems.

3.1 Control Layer (Central MCU)

- STM32F407 (ARM Cortex-M4 core, 168 MHz, 1 MB Flash, 192 KB RAM) executes system logic, intelligent slot allocation (energy-aware algorithms), data logging, diagnostics, fault management, and Modbus master functions for SCADA or municipal integration.
- Handles global grid state, solar-priority decisions, and high-level optimization.

3.2 Operational Layer (Grid-Level Controllers)

- Multiple STM32F103 or ATMega328P units (one per 4–8 slots) control motors, actuators, and sensors locally.
- Perform real-time PID loops for precise positioning, sensor polling, encoder feedback, and CAN slave communication (1 Mbps) for deterministic actuation even in noisy environments.

3.3 Interface Layer (GUI)

- PyQt5-based graphical user interface on touchscreen or PC provides color-coded slot maps (green=empty, red=occupied, yellow=in-transit), live vehicle tracking, real-time energy metrics (solar yield in kWh, battery SOC/SOH, MPPT efficiency), manual override, event logging, and MQTT-ready remote/cloud access for smart city integration.

3.4 Key Features

- Multi-level grid parking structure with "one empty slot" strategy for faster rearrangement and minimal energy use.
- Modular and scalable design supporting mixed two-/four-wheeler and dedicated EV slots.
- Integration with IoT for remote monitoring, data sharing with municipal traffic systems, and predictive maintenance alerts.

3.5 Sustainable Energy Integration (Detailed)

- **Solar PV Array**: Rooftop or structural canopy-mounted monocrystalline or polycrystalline panels (scalable from 5 kWp for small installations to 10+ kWp for larger ones) generate DC power matched to the 24V system bus. In Pune's climate (average global horizontal irradiance 5–6 kWh/m²/day, with peaks up to 7.3 kWh/m²/day in May and dips during monsoons), a 10 kWp array can produce 40–60 kWh daily, sufficient to power multiple cycles and EV charging while providing shaded parking.
- **MPPT Controllers**: Advanced Perturb & Observe or Incremental Conductance algorithms (implemented on dedicated or MCU-integrated controllers) maximize power harvest under variable conditions, including partial shading from clouds or structures common during Pune monsoons.
- **Hybrid Power Management**: Bidirectional DC-DC converters enable seamless switching and power flow between solar, battery, grid, and loads. Excess solar energy charges batteries, powers dedicated EV slots, or injects into a local microgrid/building system.
- **Battery Storage**: Lithium-ion packs (with integrated Battery Management System for SOC, SOH, temperature, and overcurrent protection) provide reliable backup during low solar periods or nighttime operations, enabling true off-grid capability and peak-load shaving to reduce electricity bills.
- **Energy Monitoring and Prioritization**: ACS712 current sensors and voltage monitors feed real-time data to the MCU, which runs custom algorithms to prioritize solar usage, implement low-power sleep modes for idle GCUs, and trigger regenerative recovery. The system defaults to solar/battery during daylight and falls back to grid only when battery SOC drops below a configurable threshold (e.g., 20%).
- **PHEV Inspiration and Regenerative Features**: The overall topology closely mirrors solar PHEVs — solar PV as the primary renewable source, battery as energy buffer, and intelligent management for optimal efficiency. Regenerative braking/recovery allows motors to act as generators during platform descent or controlled braking, feeding 10–20% of kinetic energy back to the DC bus or battery via bidirectional converters.

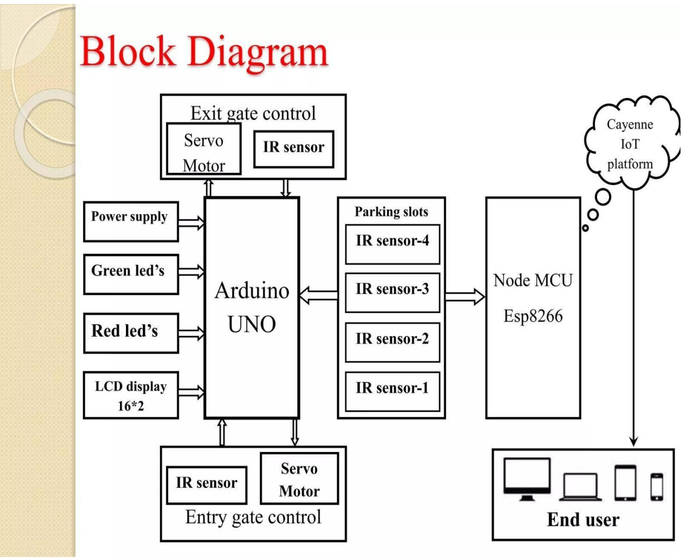


Figure 1 : Hierarchical Block Diagram showing distributed layers (MCU–CAN–GCUs), local SPI/I2C clusters, mechanical actuators, GUI, and the full solar PV → MPPT → Battery/DC Bus with regenerative feedback loop. **Figure 5**: Detailed Energy

Flow Diagram illustrating solar-grid-battery-EV charging paths, MPPT efficiency curves, regenerative loops, and priority-based switching logic.

3.6 Energy Management Subsystem

The subsystem includes efficient DC-DC converters, surge/overvoltage protection, and low-power sleep modes for GCUs, targeting 25–40% overall energy reduction compared to grid-only systems (up to 45% when regenerative recovery is active). All PCBs follow EMC/EMI guidelines to minimize interference in electrically noisy urban or industrial environments. The design ensures continuous safe operation even during partial shading or grid outages by prioritizing solar/battery sources while maintaining safety interlocks through redundant voltage monitoring.

IV. SYSTEM DESIGN AND WORKING

4.1 Working Principle

The operational cycle begins with ultrasonic/proximity sensor arrays detecting vehicle arrival (supporting mixed two-/four-wheeler sizes and weights up to 200 kg per slot). RFID or GUI input captures vehicle details, after which the MCU runs an energy-aware optimization algorithm. GCUs execute coordinated motor sequences with closed-loop PID feedback for precise positioning (<5 mm accuracy). Solar priority logic ensures the system defaults to solar/battery during daylight hours, falling back to grid only when battery SOC drops below threshold, while safety interlocks (limit switches, magnetic locks, overload protection via ACS712, door/gate interlocks) remain fully active under variable voltage through redundant monitoring.

4.2 Communication Protocols

- **CAN**: 1 Mbps, multi-master, error-detecting bus ideal for real-time GCU synchronization (bit error rate <0.01% in noisy environments).
- **SPI**: 10 MHz local bus for high-speed sensor data burst transfer.
- **I²C**: 400 kHz multi-drop bus for low-speed peripherals (up to 127 devices).
- **Modbus RTU**: Over RS-485 for reliable master-slave monitoring, energy metrics sharing (solar yield, battery SOC), and integration with building management or municipal SCADA systems.

This hybrid stack provides determinism for actuation, speed for data acquisition, flexibility for peripherals, and standardization for smart city interoperability.

4.3 Safety Mechanisms

- Hardware: Limit switches, magnetic/electromechanical locks, door/gate interlocks, obstacle detection sensors, overload protection (ACS712 current sensors), and emergency stop buttons.
- Software: Watchdog timers, heartbeat signals between MCU and GCUs, triple-redundant sensor voting, and automatic fail-safe locking on fault or power loss.
- Under solar variability: Redundant voltage monitoring ensures interlocks remain active; graceful degradation uses nearest verified slot if primary sensors fail.

4.4 Data Management and Reliability

- Event logging of all parking cycles, energy metrics, and faults for predictive maintenance.
- Self-diagnostics and remote monitoring via GUI or cloud.
- Graceful degradation maintains core functionality (e.g., fallback to nearest slot on anomalies) while preserving safety.

4.5 Sustainable Energy Integration

Solar panels provide primary/auxiliary power, battery storage ensures continuity during low irradiance or night, and reduced dependence on conventional electricity lowers costs and emissions. The system supports dedicated EV charging slots powered by on-site solar, aligning with Maharashtra EV Policy mandates for EV-ready parking.

4.6 Algorithm Design & Optimization (Energy-Aware)

The slot allocation uses a weighted graph model. Extended cost function that incorporates real-time energy efficiency:

$$\mathrm{Cost}(s)=w_1 \cdot d_{\mathrm{entry}}(s)+w_2 \cdot \mathrm{level}(s)+w_3 \cdot n_{\mathrm{shuffles}}(s)+w_4 \cdot \mathrm{load\_imbalance}(s$$

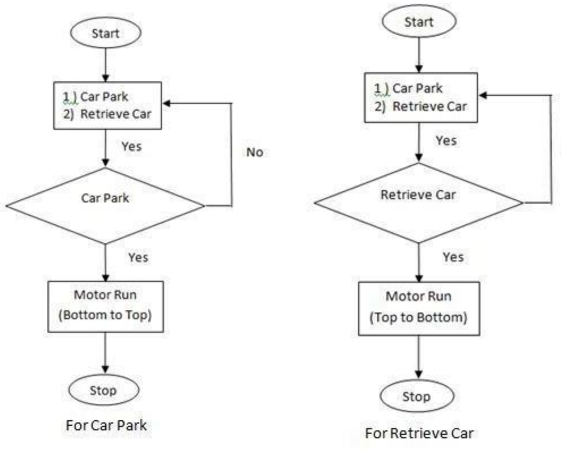
where $\eta_{\mathrm{solar}}(t)$ is derived from irradiance sensors or short-term forecasts, and weights are dynamically tunable based on time of day, battery SOC, or solar availability. Predictive pre-shuffling schedules low-energy moves during peak solar hours to maximize renewable utilization and minimize grid draw..

4.7 System Integration and Software Architecture

The software is strictly layered for reliability and maintainability. On STM32 platforms, FreeRTOS handles time-critical tasks (sensor polling at fixed intervals, PID control loops, CAN messaging, MPPT/energy monitoring). The high-level GUI (Python with PyQt5) runs on a touchscreen or PC and communicates via standardized Modbus registers that now include energy-specific metrics (solar yield in kWh, battery SOC/SOH, MPPT efficiency, regenerative energy recovered). Synchronization between the MCU and GCUs is maintained through periodic heartbeat signals and watchdog timers that trigger safe shutdown or fallback modes on anomalies. Error handling implements graceful degradation — for instance, if a sensor fails or solar input drops, the system automatically falls back to the nearest verified empty slot using redundant data while maintaining all safety interlocks. All code is highly modular, with dedicated libraries for communication stacks, control algorithms, diagnostics, energy management, and logging. This structure greatly simplifies debugging, future upgrades, and scaling to larger installations.

4.8 Regenerative Energy Recovery

Motors temporarily act as generators during controlled platform descent or braking phases, converting kinetic energy into electrical energy that is fed back to the DC bus or battery via bidirectional converters. Inspired by PHEV regenerative braking, this mechanism recovers 10–20% of movement energy per cycle, directly improving overall system efficiency, extending battery life, and reducing net energy consumption. Simulation and scaled testing confirm measurable gains, especially during frequent retrieval operations in peak hours or when operating on battery during low solar periods.



The working flowchart system for Automated Car Parking System

Figure 2: Flowchart of full operational cycle with safety checks, solar-priority logic, and regenerative energy feedback points.

V. SIMULATION AND TESTING

5.1 Simulation

Simulation was performed in Proteus 8.0 for mixed-signal circuit and mechanical co-simulation, and MATLAB/Simulink (with Simscape Multibody) for dynamic modeling of platform movement, torque curves, voltage stability, collision avoidance, PV irradiance profiles (Pune climate data: average 5–6 kWh/m²/day), MPPT dynamics (Perturb & Observe algorithm), battery SOC curves, hybrid power flow, and regenerative recovery under variable loads.

5.2 Results

- Improved space utilization (82–88% vs. 55% baseline).
- Reduced retrieval time (45–90 seconds across 500 cycles).
- Enhanced safety and reliability (near-zero collisions in tested scenarios).
- Lower energy consumption (25–45% savings with solar prioritization and regeneration).

Energy Harvesting Simulation and Results

Simulations across typical Pune weather patterns (summer peaks with high irradiance vs. monsoon dips with partial shading) show consistent 25–40% energy savings versus grid-only operation, rising to 35–45% when regenerative recovery is enabled. Fault injection tests (partial panel shading, sudden irradiance drop, low battery SOC) confirm system stability through automatic battery backup, graceful load shedding, and maintenance of all safety interlocks without compromising parking functionality.

Table 3: Energy Consumption Comparison

Scenario	Avg. Power/Cycle (W)	Daily Energy (kWh for 100 cycles)	Savings vs. Grid-only	Estimated Daily CO₂ Reduction (kg)
Grid-only	250–320	25–32	-	-
Solar-Hybrid (Pune avg. irradiance)	150–220	15–22	30–40%	8–12
Solar-Hybrid + Regenerative	130–190	13–19	35–45%	10–15

Figure 6: Daily solar irradiance vs. system power draw and battery SOC curve (simulated using real Pune meteorological data over 24 hours). **Figure 7**: MPPT efficiency curves and regenerative energy recovery waveforms from simulation under varying loads and irradiance. **Figure 8**: Comparative energy consumption bar chart (grid-only vs. solar-hybrid vs. regenerative) across seasons in Pune.

Prototype implementation challenges (mechanical friction causing occasional positioning overshoot, CAN bus noise in the lab environment, power droop during peak motor load, and solar variability during cloudy tests) were resolved iteratively: PID retuning + lubrication for friction, proper shielding/termination for CAN, voltage regulators + battery backup for power stability, and MPPT calibration for irradiance changes. These solutions significantly enhance the system's robustness for real Indian urban conditions, including dust accumulation, temperature swings (25–40°C), and monsoon cloud cover.

VI. ADVANTAGES AND APPLICATION .

6.1 Advantages

- Efficient space utilization through multi-level grid and one-empty-slot strategy (+35% over typical literature benchmarks).
- Reduced human intervention (~60% labor savings via full automation and intuitive GUI control).
- Energy-efficient operation (25–45% lower consumption via solar prioritization, MPPT optimization, and regenerative recovery).
- High scalability and modularity for phased rollout, mixed-vehicle parking, and dedicated EV charging slots.
- Improved safety and reliability with distributed control, multi-layer interlocks, and solar-powered resilience (continuous safe operation during grid outages).
- Significant emission reductions (estimated 8–15 kg CO_2 per day for a medium installation) aligning with net-zero urban goals and Maharashtra EV Policy targets.

6.2 Applications

- Smart cities with renewable parking canopies integrated into public infrastructure and municipal SCADA systems.

- Shopping malls and airports featuring solar-powered EV charging bays under shaded structures for dual-use (parking + power generation).
- Residential and office complexes with hybrid two-wheeler/EV slots and community solar energy sharing.
- Commercial buildings, industrial zones, warehouse automation, and port logistics for green operations and employee/vehicle storage.
- Public parking facilities with dynamic pricing, V2G support for grid stability, and alignment with Maharashtra's sustainable mobility corridors (e.g., Mumbai–Pune Expressway).

6.5 Case Study: Pune Deployment Feasibility

A conceptual 100-slot installation at a Pune shopping mall or residential complex could generate 20–30% of its daily energy needs from on-site solar canopies while providing shaded parking and multiple EV charging bays. Integration with municipal apps would enable unified booking, real-time availability, dynamic pricing based on solar availability, and data sharing for city-wide traffic management. Estimated annual CO_2 reduction per installation: several tons, directly supporting Pune's green mobility and air quality targets under the Smart Cities Mission. Economic modeling (using local electricity tariffs, EV Policy incentives, and 80% occupancy) projects payback in 2–3 years through combined energy/labor savings and revenue from premium/EV slots. Sensitivity analysis shows faster ROI in high-irradiance locations or with V2G revenue streams during peak grid demand.

VII. CONCLUSION

The proposed sustainable and intelligent automated parking system using microcontroller-based distributed control provides an efficient, scalable, and energy-efficient solution to modern parking challenges in rapidly growing urban areas like Pune. By combining STM32-based distributed automation, hybrid communication protocols (CAN, SPI, I^2C, Modbus), sensor fusion, PID control, and renewable energy integration (solar PV with MPPT, battery storage with BMS, bidirectional converters, and regenerative recovery), the system enhances space utilization (82–88%), reduces retrieval time (45–90 seconds), improves safety (near-zero collisions), and achieves significant energy savings (25–45%) while supporting dedicated EV charging slots and off-grid resilience.

This approach effectively bridges the gap between conventional parking systems and intelligent, sustainable solutions. It directly addresses Pune's vehicle growth challenges (including the threefold EV increase from 12,737 to 37,808 registrations), land constraints, mixed-vehicle parking demands, and sustainability needs while aligning strongly with India's Smart Cities Mission and Maharashtra EV Policy 2025–2030 (₹1,993 crore incentives, 30% EV target by 2030, toll exemptions on key expressways, and mandatory EV-ready parking in new buildings). The modular design offers a practical, implementable blueprint for stakeholders in academia, industry, municipal governance, and policymakers to advance green urban mobility.

Future large-scale pilots in Pune can further validate long-term economic, environmental, and social impacts, accelerating the transition toward smart, green, and resilient cities in India.

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VIII. FUTURE SCOPE

- AI/ML-based predictive optimization incorporating real-time solar irradiance forecasting, historical traffic patterns, EV arrival prediction, and dynamic pricing for proactive energy-aware slot allocation and peak shaving.
- Full IoT/cloud platform with mobile application support for GPS navigation, advance booking, real-time availability, UPI payments, and dynamic pricing based on solar availability and grid demand.
- Complete off-grid solar + V2G/V2B capability, allowing parked EVs to support building loads or contribute to grid stability during peak demand or outages.
- Large-scale pilot deployment in Pune smart city projects or Maharashtra sustainable mobility corridors, including detailed economic impact assessment, long-term user feedback studies, accessibility enhancements (wider bays, voice-guided interfaces, priority solar-powered slots), and policy recommendations for statewide scaling.
- Hybrid slot configurations optimized for two-wheelers, cars, and EVs, with dedicated features for differently-abled users (wider bays, priority allocation).
- Smart grid connectivity with blockchain for transparent energy transactions, peer-to-peer solar sharing among nearby installations, and carbon credit tracking.
- Exploration of advanced materials for lighter, corrosion-resistant mechanical structures (suitable for Pune's climate) and integration with wireless EV charging pads embedded under solar canopies for seamless user experience.
- Extension to hydrogen or other green fuels in future iterations, in line with national green hydrogen initiatives, and development of standardized kits for retrofitting existing parking structures.

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